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14. ABSTRACT The research effort in this project constitutes a novel hybridization of techniques developed by the PIs in recent years, concerned on one hand with finite element approaches to the modeling of contact-impact phenomena in solid and structural mechanics, and on the other with eXtended Finite Element Method (XFEM) approaches which are able to advect interfaces through finite element grids without the necessity to mesh these interfaces explicitly. The work described considered situations where a finitely deforming solid interacts with an Eulerian description of a fluid or inelastically deforming solid, and also developed and demonstrated new techniques for the description of granular and/or polycrystalline media where interfaces did not require explicit gridding, but could instead be robustly treated through new stabilized enrichment techniques, not necessitating the analyst to perform costly gridding operations.					
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**Final Project Report for
NEW NUMERICAL STRATEGIES FOR
TRANSIENT INTERACTION OF STRUCTURES WITH FLUIDS
AND SOILS
AFOSR GRANT FA9550-06-1-0108**

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1. Objectives and Accomplishments

This project focused on the development of numerical methods to describe dynamic thermomechanical interaction between structures and media which are highly compliant in a relative sense (e.g., fluids and soils). The emphasis was on interface treatment in such problems, encompassing the possibility of intense heating and/or abrasion resulting in material removal.

The overall approach amounted to a novel hybridization of techniques developed by the PIs in recent years, concerned on one hand with finite element approaches to the modeling of contact-impact phenomena in solid and structural mechanics, and on the other with eXtended Finite Element Method (XFEM) approaches which are able to advect interfaces through finite element grids without the necessity to mesh these interfaces explicitly. Major research objectives and accomplishments associated with the project, and the publicly available sources where these results were documented, are as follows:

- Extension of the XFEM paradigm to enable rigorous and general treatment of a finitely deforming solid with a nonsteady fluid flow, under modestly transient conditions. This work was reported in Jung, Dolbow & Laursen (2009), listed below in Section 5.
- Development of new surface searching algorithms, taking advantage of prior results involving mortar interface treatment and assuring the efficient determination and calculation of interface response. This work was reported in Yang & Laursen (2008), listed below in Section 5.
- To develop new stabilized XFEM approaches to multi-granular mechanics, enabling description of interface response without the need for explicit gridding of inter-granular boundaries. This work was reported in the MS thesis of Jessica Sanders, as well as in the journal article Sanders, Dolbow & Laursen (2009). Both are listed in the references below.

In addition to the above archival documents, the work encompassed by these three broad areas was disseminated at multiple talks given at national and international meetings by the PIs and their students and collaborators. These talks are listed below in Section 6.

2. Evolution of Effort and Interaction with Air Force Personnel

When compared with the original proposal, the focus of the project shifted fairly substantially with time away from interaction of solids with liquids, and more toward solid mechanical applications involving granular media. This evolution occurred both as a result of consistent communication with the Program Manager, Victor Giurgiutiu, but also as a result of our regular interaction with personnel in the Munitions Directorate at Eglin Air Force Base as this project progressed. Dr. Bill Cooper coordinate two workshops concerned with Particulate Mechanics, in January of 2007 and 2008, and the PIs participated in and were greatly influenced by both of these workshops.

This being said, however, the early work in this project (led by Y. Jung), focusing on the development of overset finite element methods for simulating the transient interaction of a “fluid” with a nonlinear structure, served to strongly guide the subsequent focus on solid-solid interactions. The work first extended existing technology in which the structure was assumed to be elastic, to one in which finite deformation plasticity was considered, considerably modifying the approach to enforcing continuity at the interface to one using a Nitsche’s method. The advantage of this approach is that it does not employ Lagrange multipliers, and thus reduces the computational cost. The convergence behavior of the method was extensively examined, and the work done in this project led directly to the work on multi-grain structures (constituting the MS degree of J. Sanders) that followed. This work was strongly driven by the interest of Munitions Directorate personnel on efficient mesoscale numerical methods for simulation of intergranular contact and slip. This work, recently documented in the MS thesis and in Sanders, Dolbow and Laursen (2009), shows conclusively that rigid interfaces in multigranular structures can be robustly treated without the need of costly explicit interface gridding by the analyst. In a follow up study, recently awarded funding by the AFOSR, the PIs will demonstrate the extension of these ideas to more intricate interface constitution and also begin efforts to extend these results across length scales.

3. Accomplishments/New Findings

The primary accomplishment of the work to date has been the development of the stabilization methods useful for both fluid/structure and solid/solid interfaces, without the need for explicit gridding of such interfaces. Methods have been demonstrated both for simple fluid-structure interaction problems, as well as for application in which the “interfaces” are grain boundaries that are not explicitly meshed by the analyst.

4. Personnel Supported

Personnel involved with this project over the past year include:

- Tod A. Laursen (PI), Professor, Department of Civil and Environmental Engineering, Duke University
- John E. Dolbow (co-PI), Associate Professor, Department of Civil and Environmental Engineering, Duke University
- Jessica Sanders, Graduate Research Assistant, Department of Civil and Environmental Engineering, Duke University
- Dr Youngjean Jung, Postdoctoral Fellow, Department of Civil and Environmental Engineering, Duke University

5. Publications

During the period of time encompassed by this award, the PIs on this grant have submitted and published several works with direct relevance to this project:

- Jung, Y., J.E. Dolbow & T.A. Laursen (2009), "Nitsche's Formulation for Force Balance and Constraint Enforcement in Fluid-Structure Interaction Using Overset Meshes," *International Journal for Numerical Methods in Engineering*, in preparation.
- Sanders, J.D., J.E. Dolbow & T.A. Laursen (2009), "On Methods for Stabilizing Constraints Over Enriched Interfaces in Elasticity," *International Journal for Numerical Methods in Engineering*, DOI: 10.1002/nme.2514.
- Sanders, J.D. (2007), *The Stabilized Enforcement of Constraints on Arbitrarily Oriented Interfaces for the Extended Finite Element Method* (MS Thesis), Department of Civil and Environmental Engineering, Duke University.
- Yang, B. & T.A. Laursen (2008), "A Contact Searching Algorithm Including Bounding Volume Trees Applied to Finite Sliding Mortar Formulations," *Computational Mechanics*, **41**, 189-205.
- Puso, M.A., T.A. Laursen & J. Solberg (2007), "A Segment-to-Segment Mortar Contact Method for Quadratic Elements and Large Deformations," *Computer Methods in Applied Mechanics and Engineering*, **197**, 555-566.
- Yang, B. & T.A. Laursen (2007), "A Large Deformation Mortar Formulation of Self Contact with Finite Sliding," *Computer Methods in Applied Mechanics and Engineering*, **197**, 756-772.
- Mourad, H.M., Dolbow J. & Harari I. (2007), "A Bubble-Stabilized Finite Element Method for Dirichlet Constraints on Embedded Interfaces," *International Journal for Numerical Methods in Engineering* **69**, 772-793.
- Kim, T.Y., Dolbow, J. & Laursen, T.A. (2007), "A Mortared Finite Element Method for Frictional Contact on Arbitrary Interfaces," *Computational Mechanics* **39**, 223-235.

6. Interactions/Transitions

6.1. Participation/presentations at meetings, conferences, etc.

Presentations made at international meetings and workshops during the award period, with particular pertinence to this project include:

- Laursen, T.A. (2009), "New Paradigms for Interface Treatments in Polycrystalline and Granular Materials," Plasticity 2009, St Thomas, Virgin Islands, January 3-9, 2009.
- Dolbow, J.E. (2008), "The Extended Finite Element Method in Applied Mechanics," ABAQUS Headquarters, Providence, RI, September 19, 2008.

- Dolbow, J.E. (2008), "On Finite Element Methods with Embedded Discontinuities for Evolving Interface Problems," Eighth World Congress on Computational Mechanics, Venice, Italy, June 30, 2008.
- Laursen, T.A. (2008), "New Developments in Computational Interface Mechanics-Perspectives Applicable to Particulate Media," Workshop on Particulate Media in Extreme Environments (PMEE 2008), University of Florida Research & Engineering Education Facility, January 30, 2008.
- Sanders, J. (2008), "Toward Stable Treatment of Fluid/Solid Interaction in the Presence of Free Surfaces," SES Meeting, University of Illinois at Urbana-Champaign, October 2008.
- Laursen, T.A. (2008), "A Stabilized Treatment of Arbitrarily Oriented Interfaces," ASME International Mechanical Engineering Congress and Exposition, Boston, Massachusetts, October 31--November 6, 2008.
- Dolbow, J.E. (2007) "Emerging Numerical Methods for Evolving Interfaces," AFOSR Workshop on Particulate Mechanics, January 23, 2007.
- Dolbow, J.E. (2007) "On Techniques for Enforcing Constraints on Embedded Interfaces," US National Congress on Computational Mechanics, San Francisco, CA, July 24, 2007.
- Jung, Y.J. (2007), "Transient Interaction of Structures with Fluids and Solids," US National Congress on Computational Mechanics, San Francisco, CA, July 24, 2007.
- Sanders, J. (2007), "Stabilized Treatment of Contact Mechanics on Arbitrarily Oriented Interfaces Using Nitsche's Method," US National Congress on Computational Mechanics, San Francisco, CA, July 24, 2007.
- Sanders, J. (2007), "A Stabilized Treatment of Arbitrarily Oriented Interfaces," COMPLAS 2007, Barcelona, Spain, September 5-7, 2007.
- Laursen, T.A. (2006), "Recent Extensions of Mortar-Based Contact Formulations: Lubrication Modeling and Parallel Implementations," IUTAM Symposium on Computational Contact Mechanics, Hannover, Germany, November 5-8, 2006.
- Laursen, T.A. (2006), "Development of Mortar Frameworks as a Foundation for Surface-Based Approaches to Contact Mechanics," International Conference on Multifield Problems, Stuttgart, Germany, October 4-6, 2006.

6.2. Consultative and advisory functions to other laboratories

Tod Laursen served as a consultant to Lawrence Livermore National Laboratory, a DOE laboratory administered by the University of California, for a one week period in 2006, and again for a week in 2007. The focus of his consulting was development of implicit finite element solution techniques for frictional contact problems, and the technical contact at LLNL was Dr. Michael Puso.

John Dolbow taught a short course on Extended Finite Element Methods (XFEM) at Sandia National Laboratories in Albuquerque, NM in June of 2006.

Additionally, with direct applicability to this project, PIs Laursen and Dolbow met with Mr. Tom Brantley of the Air Force Research Laboratory (Munitions Directorate) at Eglin

Air Force Base on February 21, 2006. The topic of discussion was modeling approaches for munitions penetration into soils. The PIs participated also in workshops for modeling of particulate media, hosted by Dr. William Cooper of Eglin, in January of 2007 and 2008.

6.3. Transitions

Our research on large deformation transient contact analysis is being used extensively by Michelin for their analysis of the rolling tire problem; technical contacts include Dr. Mike Andrews at Michelin Americas Research Corporation (Greenville, SC) and Dr. Ali Rezgui (in Ledoux, France).

7. New Discoveries, Inventions or Patent Disclosures

None to report at this time.

8. Honors/Awards

Tod Laursen was elected a Fellow of the ASME in 2008. John Dolbow received the Young Investigator Award from the International Association for Computational Mechanics (IACM) in 2008.